Lesson

17

Vapour Absorption Refrigeration Systems Based On Ammonia-Water Pair

The specific objectives of this lesson are to:

1. Introduce ammonia-water systems (*Section 17.1*)
2. Explain the working principle of vapour absorption refrigeration systems based on ammonia-water (*Section 17.2*)
3. Explain the principle of rectification column and dephlegmator (*Section 17.3*)
4. Present the steady flow analysis of ammonia-water systems (*Section 17.4*)
5. Discuss the working principle of pumpless absorption refrigeration systems (*Section 17.5*)
6. Discuss briefly solar energy based sorption refrigeration systems (*Section 17.6*)
7. Compare compression systems with absorption systems (*Section 17.7*)

At the end of the lecture, the student should be able to:

1. Draw the schematic of a ammonia-water based vapour absorption refrigeration system and explain its working principle
2. Explain the principle of rectification column and dephlegmator using temperature-concentration diagrams
3. Carry out steady flow analysis of absorption systems based on ammonia-water
4. Explain the working principle of Platen-Munter’s system
5. List solar energy driven sorption refrigeration systems
6. Compare vapour compression systems with vapour absorption systems

17.1. Introduction

Vapour absorption refrigeration system based on ammonia-water is one of the oldest refrigeration systems. As mentioned earlier, in this system ammonia is used as refrigerant and water is used as absorbent. Since the boiling point temperature difference between ammonia and water is not very high, both ammonia and water are generated from the solution in the generator. Since presence of large amount of water in refrigerant circuit is detrimental to system performance, rectification of the generated vapour is carried out using a rectification column and a dephlegmator. Since ammonia is used as the refrigerant, these systems can be used for both refrigeration and air conditioning applications. They are available in very small (as pumpless systems) to large refrigeration capacities in applications ranging from domestic refrigerators to large cold storages. Since ammonia is not compatible with materials such as copper or brass, normally the entire system is fabricated out of steel. Another important difference between this system and water-lithium bromide systems is in the operating pressures. While water-lithium bromide systems operate under very low (high vacuum) pressures, the ammonia-water system is operated at pressures much higher than atmospheric. As a result, problem of air leakage into the system is eliminated. Also this system does not suffer from the problem of crystallization encountered in water-lithium bromide systems. However, unlike water, ammonia is both toxic and flammable. Hence, these systems need safety precautions.

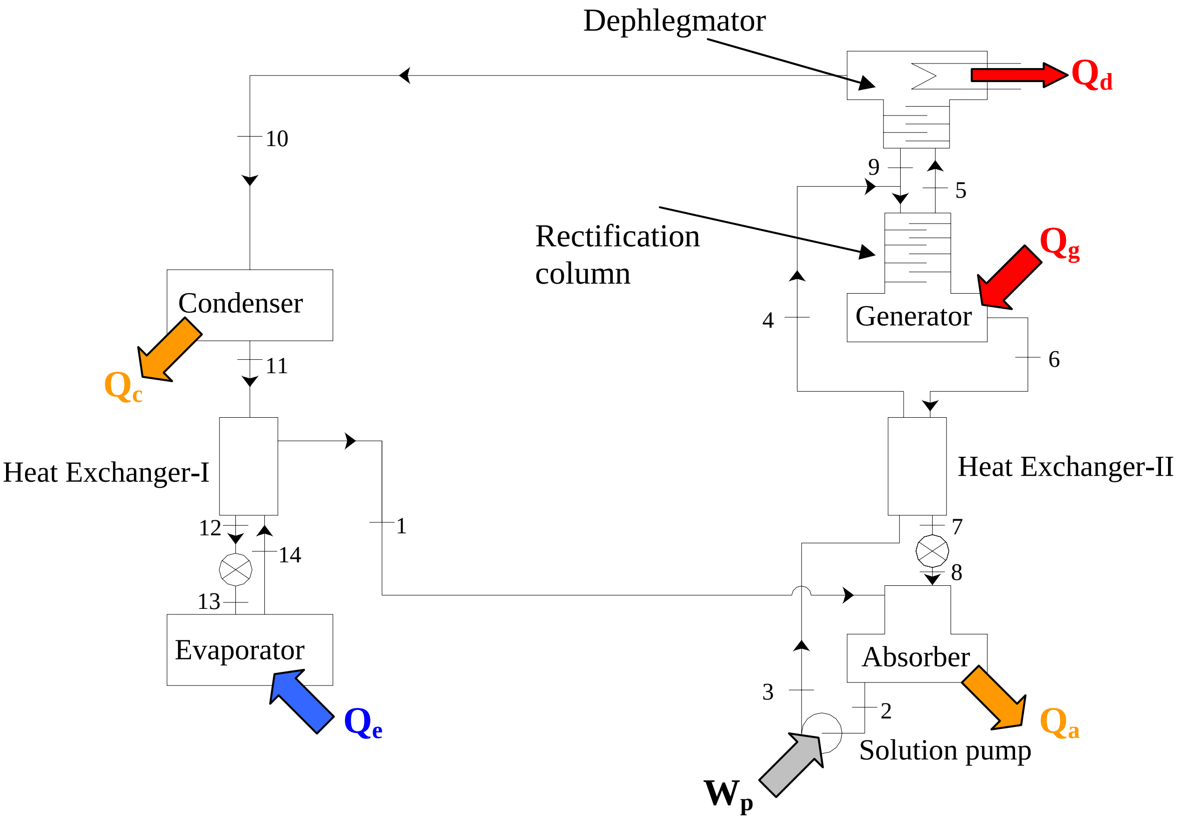

***Fig.17.1**: Schematic of NH_3-H_2O based vapour absorption refrigeration system*

17.2. Working principle

Figure 17.1 shows the schematic of an ammonia-water absorption refrigeration system. Compared to water-lithium bromide systems, this system uses three additional components: **a rectification column**, **a dephlegmator** and **a subcooling heat exchanger** (Heat Exchanger-I). As mentioned before, the function of rectification column and dephlegmator is to reduce the concentration of water vapour at the exit of the generator. Without these the vapour leaving the generator may consist of **five to ten percent of water**. However, with rectification column and dephlegmator the concentration of water is **reduced to less than one percent**. The rectification column could be in the form of a packed bed or a spray column or a perforated plate column in which the vapour and solution exchange heat and mass. It is designed to provide a large residence time for the fluids so that high heat and mass transfer rates could be obtained. The subcooling heat exchanger, which is normally of counterflow type is used to increase the refrigeration effect and to ensure liquid entry into the refrigerant expansion valve.

As shown in the figure, low temperature and low pressure vapour (almost pure ammonia) at state 14 leaves the evaporator, exchanges heat with the condensed liquid in Heat Exchanger-I and enters the absorber at state 1. This refrigerant is absorbed by the weak solution (weak in ammonia) coming from the solution expansion valve, state 8. The heat of absorption, Q_a is rejected to an external heat sink. Next the strong solution that is now rich in ammonia leaves the absorber at state 2 and is pumped by the solution pump to generator pressure, state 3. This high pressure solution is then pre-heated in the solution heat exchanger

(Heat Exchanger-II) to state 4. The preheated solution at state 4 enters the generator and exchanges heat and mass with the hot vapour flowing out of the generator in the rectification column. In the generator, heat is supplied to the solution (Q_g). As a result vapour of ammonia and water are generated in the generator. As mentioned, this hot vapour with five to ten percent of water exchanges heat and mass with the rich solution descending from the top. During this process, the temperature of the vapour and its water content are reduced. This vapour at state 5 then enters the dephlegmator, where most of the water vapour in the mixture is removed by cooling and condensation. Since this process is exothermic, heat (Q_d) is rejected to an external heat sink in the dephlegmator. The resulting vapour at state 10, which is almost pure ammonia (mass fraction greater than 99 percent) then enters the condenser and is condensed by rejecting heat of condensation, Q_c to an external heat sink. The condensed liquid at state 11 is subcooled to state 12 in the subcooling heat exchanger by rejecting heat to the low temperature, low pressure vapour coming from the evaporator. The subcooled, high pressure liquid is then throttled in the refrigerant expansion valve to state 13. The low temperature, low pressure and low quality refrigerant then enters the evaporator, extracts heat from the refrigerated space (Q_e) and leaves the evaporator at state 14. From here it enters the subcooling heat exchanger to complete the refrigerant cycle. Now, the condensed water in the dephlegmator at state 9 flows down into the rectifying column along with rich solution and exchanges heat and mass with the vapour moving upwards. The hot solution that is now weak in refrigerant at state 6 flows into the solution heat exchanger where it is cooled to state 7 by preheating the rich solution. The weak, but high pressure solution at state 7 is then throttled in the solution expansion valve to state 8, from where it enters the absorber to complete its cycle.

As far as various energy flows out of the system are concerned, heat is supplied to the system at generator and evaporator, heat rejection takes place at absorber, condenser and dephlegmator and a small amount of work is supplied to the solution pump.

17.3. Principle of rectification column and dephlegmator

Figure 17.2 shows the schematic of the rectification system consisting of the generator, rectifying column and dephlegmator. As shown in the figure, strong solution from absorber enters at the rectification column, vapour rich in ammonia leaves at the top of the dephlegmator and weak solution leaves from the bottom of the generator. A heating medium supplies the required heat input Q_g to the generator and heat Q_d is rejected to the cooling water in the dephlegmator.

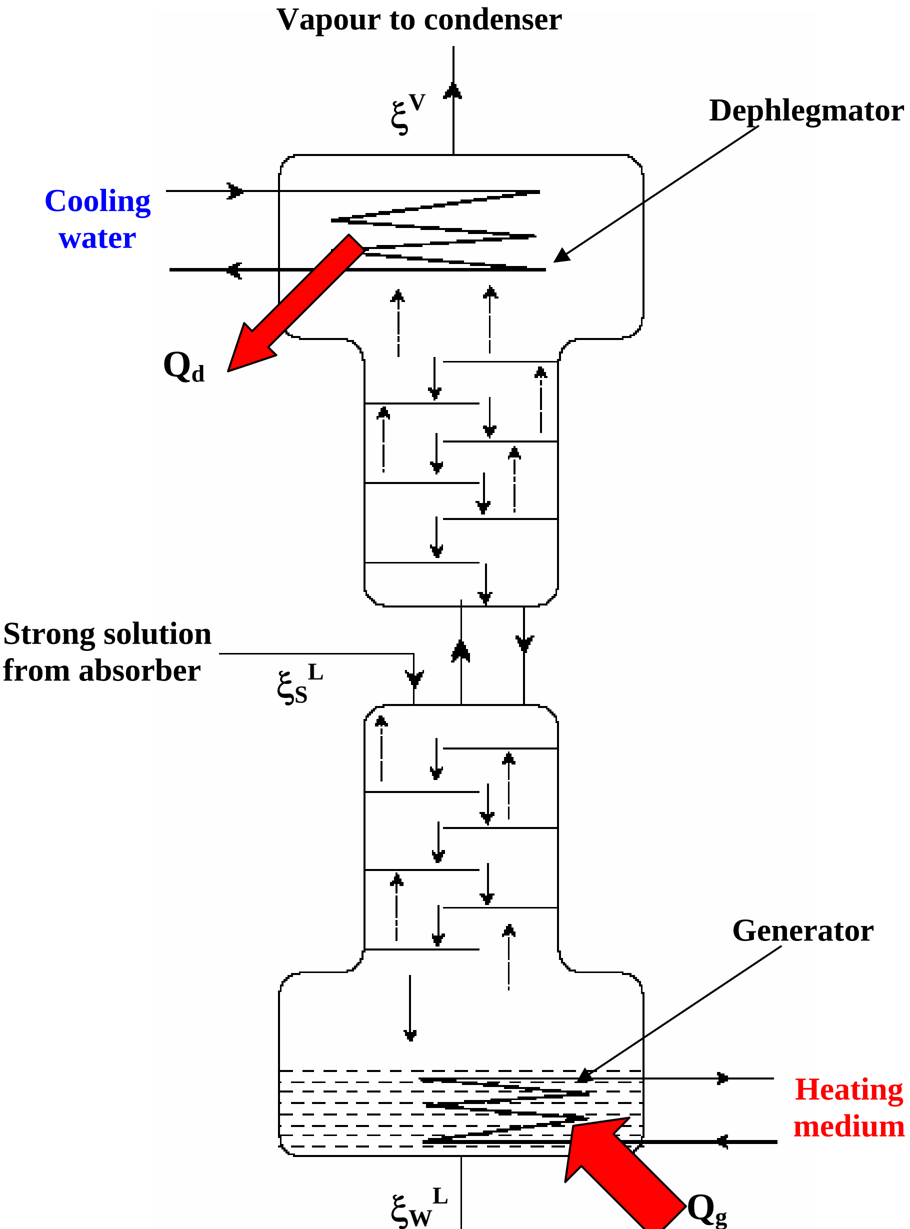

Fig.17.2*: Schematic of the rectification column used in NH_3-H_2O systems*

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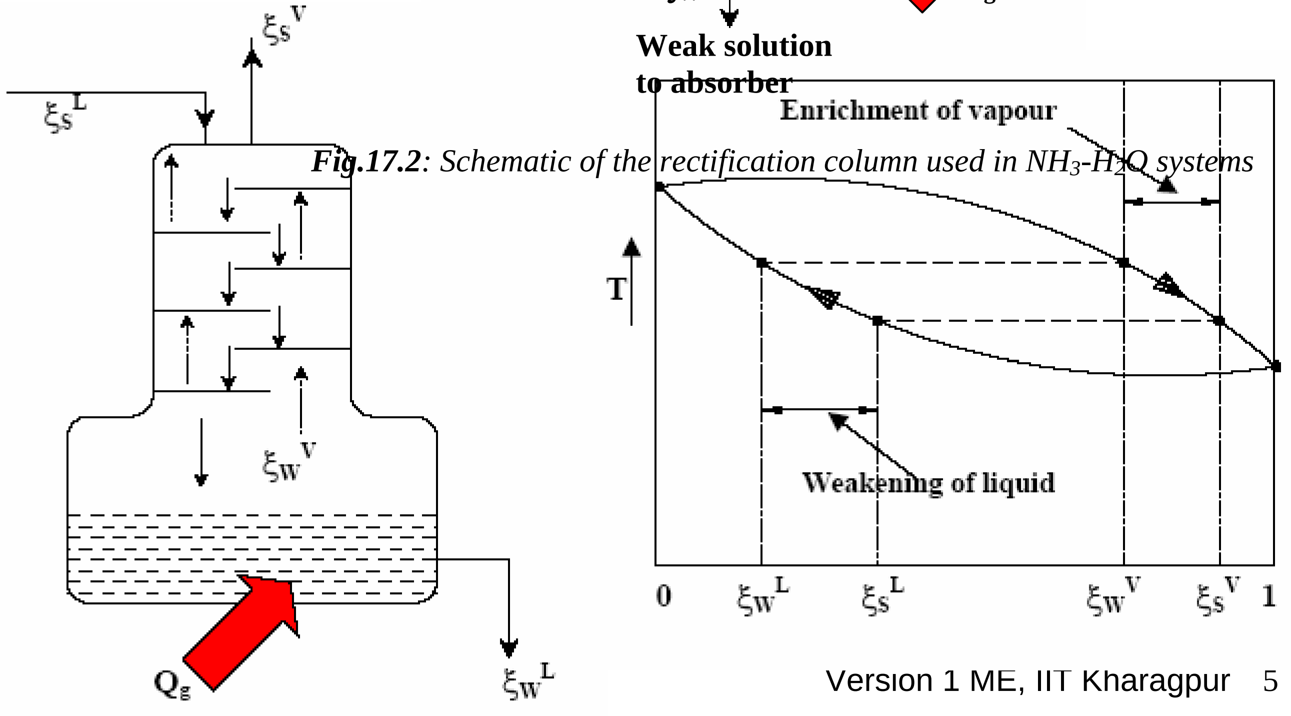

Fig.17.3*: Rectification process in the generator*

17.3 shows the schematic of the generator with lower portion of the rectification column and the process that takes place in this column on temperature-composition diagram. As shown, in this column the ascending vapour generated in the generator and initially at a mass fraction of ξ_W^V is enriched in ammonia to ξ_S^V as it exchanges heat and mass with the descending rich solution, which had an initial concentration of ξ_S^L. During this process the solution becomes weak as ammonia is transferred from liquid to vapour and water is transferred from vapour to liquid. In the limit with infinite residence time, the vapour leaves at mass fraction ξ_S^V that is in equilibrium with the strong solution. It can also be seen that during this process, due to heat transfer from the hot vapour to the liquid, the solution entering the generator section is preheated. This is beneficial as it reduces the required heat input in the generator.

Figure 17.4 shows the principle of dephlegmator (or reflux condenser) in which the ascending vapour is further enriched. At the top of the dephlegmator, heat is removed from the vapour so that a part of the vapour condenses (reflux). This reflux that is cooler, exchanges heat with the hotter vapour ascending in the column. During this process water vapour is transferred from the vapour to the liquid and ammonia is transferred from liquid to the vapour as shown in Fig. 17.4. As a result the vapour leaves the rectification column in almost pure ammonia form with a concentration of ξ^V.

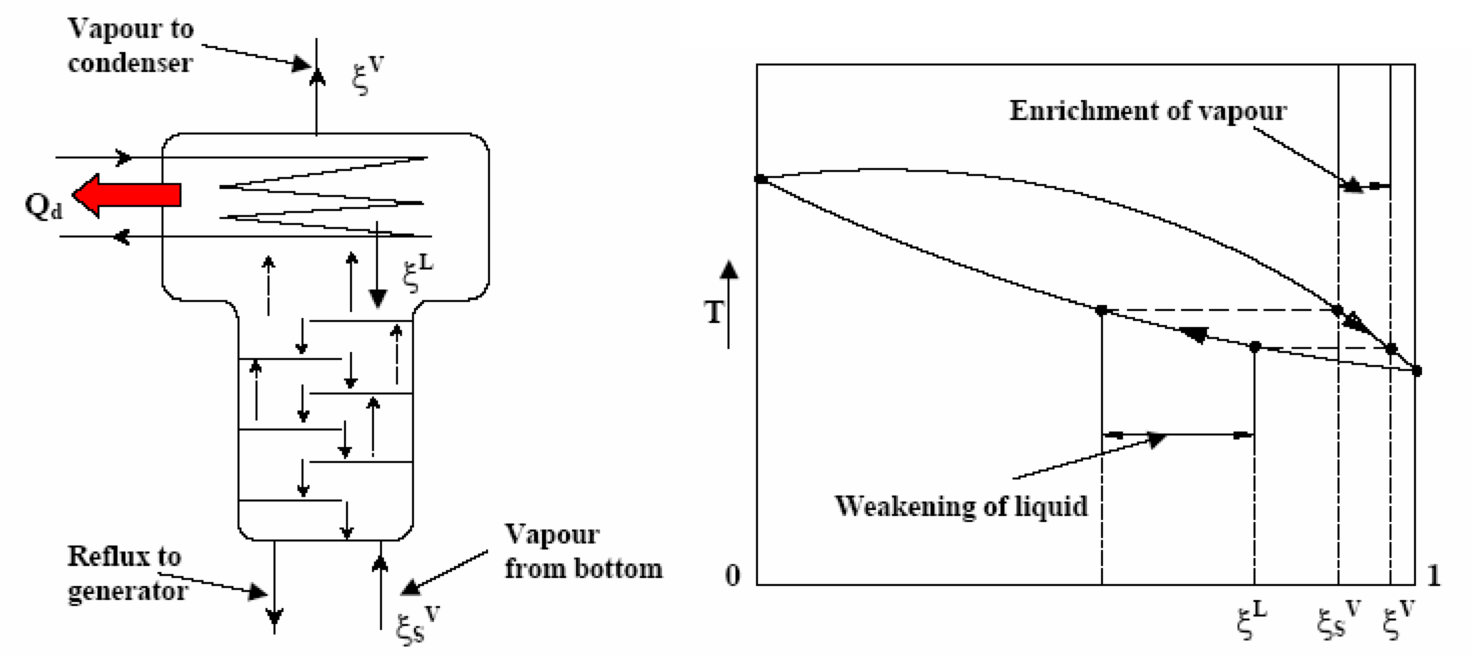

Fig.17.4: *Principle of dephlegmator*

17.4. Steady-flow analysis of the system

The analysis is carried out in a manner similar to water-lithium bromide system, i.e., by applying steady flow mass and energy balance to each component.

However, since the composition is defined on the basis of ammonia in the solution, the terms weak and strong solution concentrations have different meanings. In ammonia-water systems, strong solution means solution that is rich in ammonia, consequently, weak solution refers to solution that is weak in ammonia.

The circulation ratio λ is defined as the **ratio of weak solution to refrigerant flow rate**, i.e.,

$$\lambda = \frac{\dot{m}_{ws}}{\dot{m}} \Rightarrow \dot{m}_{ws} = \lambda \dot{m} \text{ and } \dot{m}_{ss} = (1+\lambda)\dot{m} \tag{17.1}$$

By applying mass balance across the absorber and assuming the amount of water vapour in the refrigerant vapour at the exit of evaporator as negligible, the circulation ratio can be shown to be:

$$\lambda = \frac{1-\xi_s}{\xi_s - \xi_w} \tag{17.2}$$

where ξ_S and ξ_W are the mass fractions of the strong and weak solutions leaving the absorber and entering the absorber, respectively.

Mass and energy balance equations for all the components are same as those of water-lithium bromide system, however, the thermal energy input to the generator will be different due to the heat transfer at the dephlegmator. Taking a control volume that includes entire rectifying column (generator + rectification column + dephlegmator) as shown in Fig.17.5, we can write the energy equation as:

$$Q_g - Q_d = \dot{m}_{10} h_{10} + \dot{m}_6 h_6 - \dot{m}_4 h_4 \tag{17.3}$$

writing the mass flow rates of strong (point 4) and weak (point 6) solutions in terms of refrigerant flow rate and mass fractions, we can write the above equation as:

$$Q_g - Q_d = \dot{m}\left[(h_{10} - h_4) + \lambda(h_6 - h_4)\right] \tag{17.4}$$

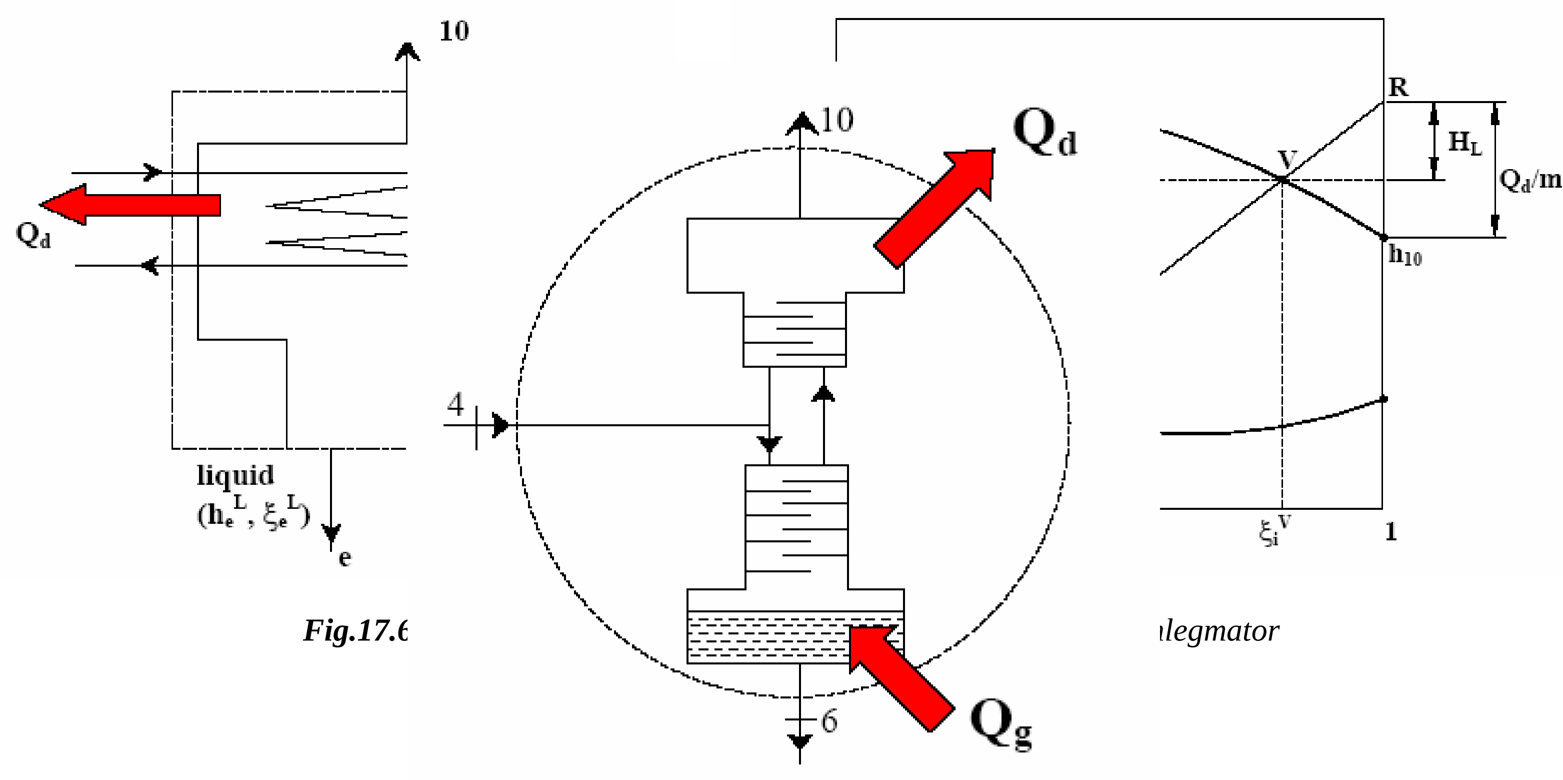

Fig.17. *legmator*

Fig.17.5*: Control volume for calculating heat input to the system*

From the above expression Q_g-Q_d can be calculated, however, to find COP we need to know Q_g. This requires estimation of heat transferred in the dephlegmator, Q_d. This can be obtained by applying mass and energy balance across the dephlegmator section as shown in Fig.17.6. From these equations it can be shown that for **ideal rectification with the exit vapour being pure ammonia**, the heat transferred in the dephlegmator is given by:

$$\left(\mathbf{Q_d}\Big/\dot{\mathbf{m}}\right)=\left[\mathbf{h_i}^{\mathbf{V}}-\mathbf{h_{10}}+\left(\frac{\mathbf{1}-\xi_{\mathbf{i}}{}^{\mathbf{V}}}{\xi_{\mathbf{i}}{}^{\mathbf{V}}-\xi_{\mathbf{e}}{}^{\mathbf{L}}}\right)\left(\mathbf{h_i}^{\mathbf{V}}-\mathbf{h_e}^{\mathbf{L}}\right)\right]=(\mathbf{h_i}^{\mathbf{V}}-\mathbf{h_{10}})+\mathbf{H_L} \quad (17.5)$$

$$\mathbf{H_L}=\left(\frac{\mathbf{1}-\xi_{\mathbf{i}}{}^{\mathbf{V}}}{\xi_{\mathbf{i}}{}^{\mathbf{V}}-\xi_{\mathbf{e}}{}^{\mathbf{L}}}\right)\left(\mathbf{h_i}^{\mathbf{V}}-\mathbf{h_e}^{\mathbf{L}}\right) \quad (17.6)$$

The above equation is applicable at any section across the upper rectification column. If the process is plotted on enthalpy-composition diagram as shown in Fig.17.6, it can be easily seen that the ordinate of point R (called as Pole of the rectifier) is equal to $\left(Q_d\Big/\dot{m}\right)+h_{10}$ as H_L is equal to $H_L=\left(\frac{1-\xi_i{}^V}{\xi_i{}^V-\xi_e{}^L}\right)\left(h_i{}^V-h_e{}^L\right)$.

It should be noted that the line joining points L and V on enthalpy-composition diagram need not be an isotherm. In other words, points V and L need not be in equilibrium with each other, but they have to satisfy the mass and energy balance across the control volume.

For rectification to proceed in the column, it is essential that at every cross-section, the temperature of the vapour should be higher than that of the liquid. This is possible only if the slope of the line passing through pole R is always steeper than the isotherm in the two-phase region passing through h_e^L and ξ_e^L. This can be ensured by placing the pole R at a sufficiently high level on the $\xi = 1$ axis. This in turn fixes the minimum amount of reflux and the heat rejected at the dephlegmator. It is observed that for ammonia-water mixtures the condition that the vapour must always be warmer than the liquid is satisfied by drawing a straight line through R steeper than the isotherm passing through the strong solution feed point (point 4). This way the position of R is fixed and from this, the minimum amount of dephlegmator heat $Q_{d,min}$ is determined. However, the actual dephlegmator heat $Q_{d,act}$ will be larger than the minimum amount, and the ratio of minimum dephlegmator heat to actual dephlegmator heat is called as rectifier efficiency, η_R given by:

$$\eta_R = \frac{Q_{d,min}}{Q_{d,act}} \tag{17.7}$$

The rectifier efficiency depends on the design of contact surface used for the rectification column.

Sometimes, in the absence of required data, the COP is calculated by assuming that the dephlegmator heat is a certain percentage of generator heat (**usually 10 to 20 percent**).

17.5: Pumpless vapour absorption refrigeration systems

Conventional absorption refrigeration systems use a mechanical pump for pumping the solution from absorber pressure to generator pressure. However, there are also absorption refrigeration systems that do not require a mechanical pump. These systems offer several advantages over conventional systems such as:

i. High reliability due to absence of moving parts
ii. Very little maintenance
iii. Systems require only low grade thermal energy, hence no need for any grid power
iv. Silent operation

Due to the above advantages the pumpless systems find applications such as refrigerators for remote and rural areas, portable refrigerators, refrigerators for luxury hotel rooms etc.

Several pumpless systems using both water-lithium bromide and ammonia-water have been developed over the last many decades. However, among these the most popular and widely used system is the one known as Platen-Munters system or Triple Fluid Vapour Absorption Refrigeration System (TFVARS). As mentioned in the introduction, this system was developed by Platen and Munters of Sweden in 1930s. It uses ammonia as refrigerant and water as absorbent and hydrogen as an inert gas. Unlike conventional systems, the total pressure is constant throughout the Platen-Munters system, thus eliminating the need for mechanical pump or compressor. To allow the refrigerant (ammonia) **to evaporate at low temperatures in the evaporator**, a third inert gas (hydrogen) is introduced into the evaporator-absorber of the system. Thus even though the total pressure is constant throughout the system, the partial pressure of ammonia in evaporator is much smaller than the total pressure due to the presence of hydrogen.

For example: if the total pressure of the system is 15 bar, then the condenser temperature will be 38.7°C (saturation temperature at 15 bar). If contribution of hydrogen to total pressure in the evaporator is 14 bar, then the partial pressure of ammonia in evaporator is 1 bar, hence ammonia can evaporate at –33°C (saturation temperature at 1 bar), thus providing refrigeration effect at very low temperatures.

The liquid **ammonia in the evaporator cannot boil in the evaporator as its partial pressure is lower than the total pressure** (no vapour bubbles form). The **ammonia simply evaporates** into the hydrogen gas (just as liquid water evaporates into the atmosphere) as long as hydrogen gas is not saturated with ammonia. The ammonia vapour generated is carried away by the process of diffusion, hence Platen-Munters systems are also called as **diffusion-absorption systems**.

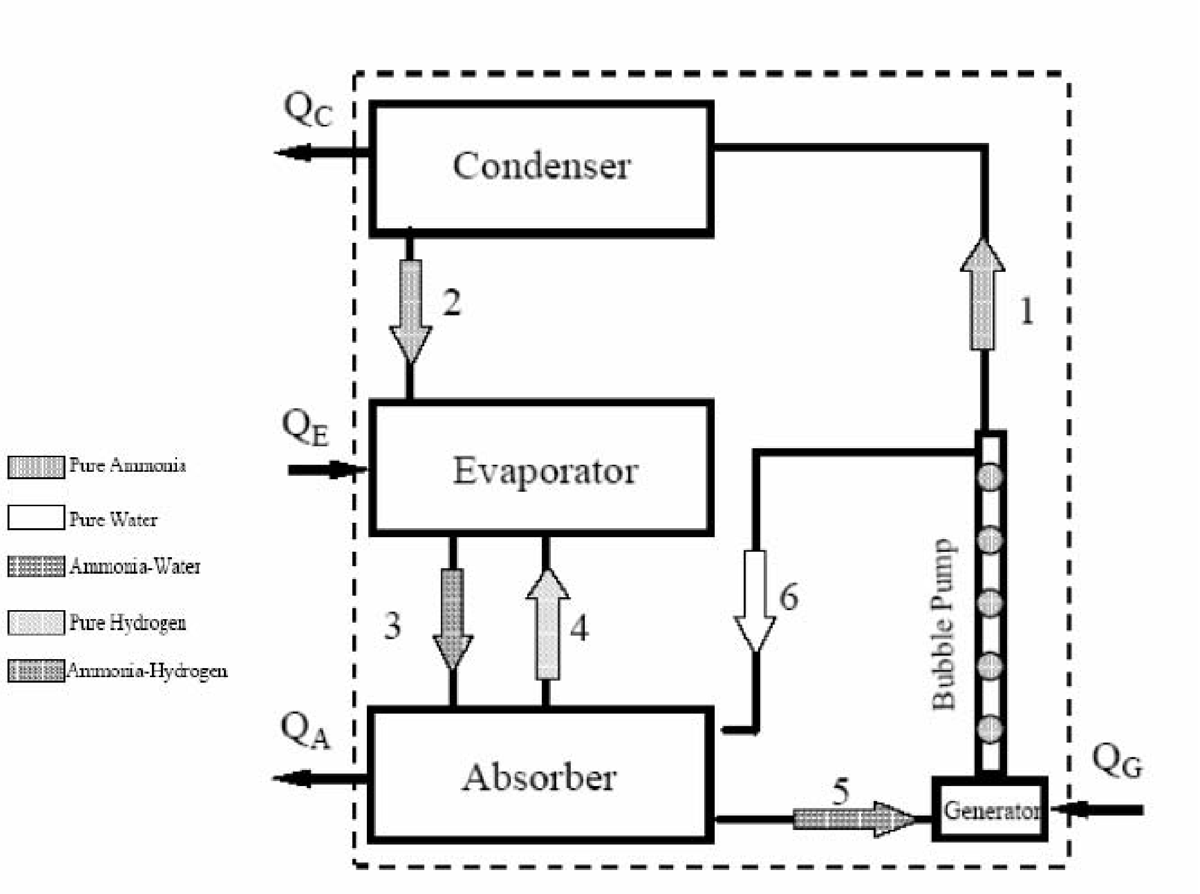

Fig.17.8*: Working principle of Platen-Munters system*

Figure 17.8 shows the schematic of a triple-fluid Platen-Munters system. Starting with the strong solution at the exit of the absorber (state 5), heat is supplied in the generator; ammonia vapour is generated as a result. The vapour generated moves up through the bubble pump due to buoyancy. As the vapour moves up it carries the weak solution to the top of the bubble pump. At the top, the weak solution and vapour are separated. The refrigerant vapour at state 1 flows into the condenser, where it condenses by rejecting heat to the heat sink (condensation takes place at high temperature as ammonia pressure is equal to the total pressure). The condensed liquid at state 2 flows into evaporator. As it enters into the evaporator its pressure is reduced to its partial pressure at evaporator temperature due to the presence of hydrogen gas in the evaporator. Due to the reduction in pressure, the ammonia evaporates by taking heat from the refrigerated space. The ammonia vapour diffuses into the hydrogen gas. Since the mixture of ammonia and hydrogen are cooler, it flows down into the absorber due to buoyancy. In the absorber, the ammonia vapour is absorbed by the weak solution coming from the bubble pump. Heat of absorption is rejected to the heat sink. Due to this, the temperature of hydrogen gas increases and it flows back into the evaporator due to buoyancy. Thus the circulation of fluids throughout the system is maintained due to buoyancy effects and gravity.

Due to the evaporation process (as against boiling in conventional systems) the temperature of the evaporating liquid changes along the length of the evaporator. **The coldest part is obtained at the end where hydrogen enters the evaporator as the partial of ammonia is least at this portion**. This effect can be used to provide two temperature sections in the evaporator for example: one for frozen food storage and the other for fresh food storage etc.

A **liquid seal** is required at the end of the condenser to prevent the entry of hydrogen gas into the condenser. Commercial Platen-Munters systems are made of all steel with welded joints. Additives are added to minimize corrosion and rust formation and also to improve absorption. Since there are no flared joints and if the quality of the welding is good, then these systems become extremely rugged and reliable. The Platen-Munters systems offer low COPs (of the order of 0.2) due to energy requirement in the bubble pump and also due to losses in the evaporator because of the presence of hydrogen gas. In addition, since the circulation of fluids inside the system is due to buoyancy and gravity, the heat and mass transfer coefficients are relatively small, further reducing the efficiency. However, these systems are available with a wide variety of heat sources such as electrical heaters (in small hotel room systems), natural gas or LPG gas, hot oils etc. Figure 17.9 shows the schematic of the refrigeration system of a small commercial Platen-Munters system.

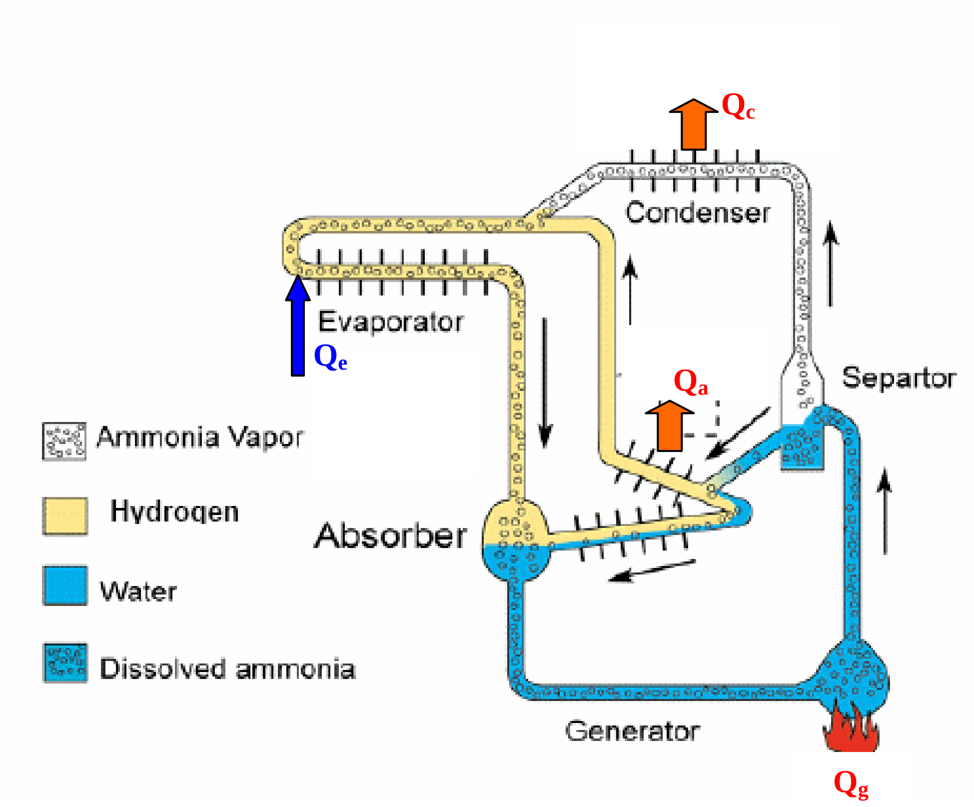

***Fig.17.9**: Refrigeration circuit of a small diffusion-absorption (Platen-Munters) system*

It is interesting to know that Albert Einstein along with Leo Szilard had obtained a US patent for a pumpless absorption refrigeration system in 1930. The principle of operation of this system is entirely different from that of Platen-Munters system. In Einstein's system, butane is used as the refrigerant, while ammonia is used as pressure equalizing fluid in evaporator. Water is used as the absorbent for the pressure equalizing fluid. However, unlike Platen-Munter's system, Einstein's system has not been commercialized. Recently attempts have been made to revive Einstein's cycle.

17.6: Solar energy driven sorption systems

In principle, solar energy can be used to drive any type of refrigeration system: compression or absorption. However, in most of the cases, the direct utilization of solar thermal energy for running refrigeration systems is more efficient. Thus solar energy based heat operated systems are attractive. Again solar energy can be used to run a conventional absorption system with solution pump or a pumpless absorption or adsorption system.

Solar energy driven adsorption systems that use a solid adsorbent in place of a liquid absorbent offer certain advantages. The solid sorption systems also known as dry absorption systems do not have a solution circuit as the vapour/gas is directly absorbed and desorbed by a solid. Notable among the dry absorption types are the systems based on **water-zeolites/silica gel**, **methanol-activated carbon**, **ammonia-calcium chloride**, **sulphur dioxide-sulphites**, **carbon dioxide-carbonates** and **hydrogen-metal hydrides**. However, some practical design problems such as: smaller specific power outputs, poor heat and mass transfer characteristics of the solid absorbents, unwanted side reactions, undesired decomposition of reacting materials, swelling of solid material and corrosion of the structural materials due to the nature of the reacting materials/reactions hamper the development of solid sorption systems on commercial scale. Several successful attempts have been made to build refrigeration systems that run on solar energy only. However, several practical problems related to their cost, performance and reliability hamper the wide-spread use of solar energy driven refrigeration systems.

17.7: Comparison between compression and absorption refrigeration systems

Table 17.1 shows a comparison between compression and absorption refrigeration systems.

Compression systems	Absorption systems
Work operated	Heat operated
High COP	Low COP (currently maximum ≈ 1.4)
Performance (COP and capacity) very sensitive to evaporator temperatures	Performance not very sensitive to evaporator temperatures
System COP reduces considerably at part loads	COP does not reduce significantly with load
Liquid at the exit of evaporator may damage compressor	Presence of liquid at evaporator exit is not a serious problem
Performance is sensitive to evaporator superheat	Evaporator superheat is not very important
Many moving parts	Very few moving parts
Regular maintenance required	Very low maintenance required
Higher noise and vibration	Less noise and vibration
Small systems are compact and large systems are bulky	Small systems are bulky and large systems are compact
Economical when electricity is available	Economical where low-cost fuels or waste heat is available

***Table 17.1**: Comparison between compression and absorption systems*

Questions and answers:

1. In an ammonia-water system a rectification column is used mainly to:

a) To improve the COP of the system
b) To reduce the operating pressures
c) To minimize the concentration of water in refrigeration circuit
d) All of the above

Ans.: c)

2. In a reflux condenser:

a) Heat is extracted so that the vapour leaving is rich in ammonia
b) Heat is supplied so that the vapour leaving is rich in ammonia
c) Heat is extracted so that the vapour leaving is rich in water
d) Heat is supplied so that the vapour leaving is rich in ammonia

Ans.: a)

3. Due to the requirement of rectification:

a) The required generator pressure increases
b) The required generator temperature increases
c) The required generator heat input increases
d) All of the above

Ans.: c)

4. In pumpless vapour absorption refrigeration systems:

a) The evaporation process is non-isothermal
b) The system pressure is almost same everywhere
c) A pressure equalizing fluid is required to increase condenser pressure
d) A pressure equalizing fluid is required to increase evaporator pressure

Ans.: a), b) and d)

5. Which of the following statements regarding pumpless systems are TRUE:

a) Pumpless systems can use a wide variety of heat sources
b) Pumpless systems are silent, reliable and rugged
c) Pumpless systems offer high COPs
d) Pumpless systems operate at very low pressures

Ans.: a) and b)

6. Compared to compression systems, the performance of absorption systems:

a) Is very sensitive to evaporator temperature
b) Is not sensitive to load variations
c) Does not depend very much on evaporator superheat
d) All of the above

Ans.: b) and c)

7. Compared to compression systems, absorption systems:

a) Contain very few moving parts
b) Require regular maintenance
c) Offer less noise and vibration
d) Are compact for large capacities

Ans.: a), c) and d)

8. A vapour absorption refrigeration system based on ammonia-water (Figure 17.1) has refrigeration capacity of **100 TR**. The various state properties of the system shown below are given in the table. Taking the heat rejection rate in the reflux condenser (Q_d) as **88 kW**, find a) The mass flow rates of solution through the evaporator, strong solution and weak solution; b) Enthalpy values not specified in the table and c) Heat transfer rates at condenser, absorber and generator and solution pump work d) System COP

State point	P, bar	T, ^oC	Concentration (X), kg of NH_3/kg of solution	Enthalpy, kJ/kg
1	2.04	13.9	0.996	
2	2.04	26.1	0.408	-58.2
3	13.61	26.1	0.408	-56.8
4	13.61	93.3	0.408	253.6
6	13.61	115.6	0.298	369.9
7	13.61	36.1	0.298	
8	2.04	36.1	0.298	
10	13.61	54.4	0.996	1512.1
11	13.61	36.1	0.996	344.3
12	13.61	30.0	0.996	318.7
13	2.04	-17.8	0.996	
14	2.04	4.4	0.996	1442.3

Ans.:

a) Mass flow rate through evaporator, m_1 is given by:

$$m_1 = \left(\frac{Q_e}{h_{14} - h_{13}}\right) = \left(\frac{Q_e}{h_{14} - h_{12}}\right) = \left(\frac{3.517 \text{ X } 100}{1442.3 - 318.7}\right) = 0.313 \text{ kg/s} \qquad \textbf{(Ans.)}$$

Circulation ratio λ is given by:

$$\lambda = \left(\frac{m_{ws}}{m_1}\right) = \left(\frac{\xi_{10} - \xi_7}{\xi_7 - \xi_8}\right) = 5.345$$

Therefore, mass flow rate of weak solution, $\mathbf{m_{ws} = m_1 \, X \, \lambda = 1.673}$ **kg/s** **(Ans.)**

mass flow rate of strong solution, $\mathbf{m_{ss} = m_1 \, X \, (1+\lambda) = 1.986}$ **kg/s** **(Ans.)**

b) State points 1, 7,8 and 13:

From energy balance across Heat Exchanger –I;

$(h_{11} - h_{12}) = (h_1 - h_{14}) \Rightarrow \mathbf{h_1 = h_{14} + (h_{11} - h_{12}) = 1467.9}$ **kJ/kg** **(Ans.)**

From energy balance across solution heat exchanger:

$m_{ss}(h_4 - h_3) = m_{ws}(h_6 - h_7) \Rightarrow \mathbf{h_7 = 1.43}$ **kJ/kg** **(Ans.)**

Since expansion through expansion valves is isenthalpic,

$\mathbf{h_8 = h_7 = 1.43}$ **kJ/kg** **(Ans.)**

$\mathbf{h_{12} = h_{13} = 318.7}$ **kJ/kg** **(Ans.)**

c) From energy balance:

Heat transfer rate at condenser, $\mathbf{Q_c = m_{10}(h_{10} - h_{11}) = 365.5}$ **kW** **(Ans.)**

Heat transfer rate at absorber, $\mathbf{Q_a = m_1h_1+m_8h_8-m_2h_2) = 577.4}$ **kW** **(Ans.)**

Heat transfer rate at generator, $\mathbf{Q_g = m_{10}h_{10}+m_6h_6+Q_d-m_4h_4) = 676.5}$ **kW** **(Ans.)**

Power input to pump, $\mathbf{W_p = m_2(h_3 - h_2) = 2.78}$ **kW** **(Ans.)**

System COP is given by:

$$\mathbf{COP} = \left(\frac{Q_e}{Q_g + W_p}\right) = \left(\frac{351.7}{676.5 + 2.78}\right) = 0.518 \qquad \textbf{(Ans.)}$$

Comments:

1. It can be seen that compared to heat input to the system at the generator, the work input to the system is almost negligible (less than 0.5 percent)
2. The system COP is reduced as the required heat input to the generator increases due to heat rejection at dephlegmator. However, this cannot be avoided as rectification of the vapour is required. However, it is possible to analyze the rectification process to minimize the heat rejection at the dephlegmator